The Lunar Mare

Marius Hills
- Marius Q
- Marius L

Pit location → Sinuous Rilles

Rima Galilaei

20 km

5 km

64 m
Near (left) and far (right) sides of the Moon

Taken by the Lunar Reconnaissance Orbiter
Nearside-Farside Dichotomy

- Crust is thicker on the farside – fewer basalt eruptions.
- Center of Mass offset from Center of Figure.
- But why??

GRAIL Crustal Thickness; LRO/LOLA Topography.
Mantle Density: 3220 kg m⁻³; Crustal Porosity = 12%.
Types of Basalts

Mare Basalts because the dark areas were described as “seas” – Latin = Maria/Mare

Two basic types:

• Volcanic glasses
• Crystalline basalts

Very Low-Ti (VLT): <1 wt% TiO₂
Low-Ti: 1-6 wt% TiO₂
High-Ti: >6 wt% TiO₂
Volcanic Glasses

High-Ti orange glasses from Apollo 17

Sample 74220 from Apollo 17

Apollo 17 Station 4, Shorty Crater, actual color
Volcanic Glasses

Also VLT green glasses from Apollo 15
36 years after collection, Apollo volcanic glasses shown to contain water and other volatiles.

**Water in the Glass Parent Magma:** 260-745 ppm


**Melt Inclusions in Olivine from A-17 Orange glass:** 1000 ppm H₂O

Hauri et al. (2011) Science 333, 213-215

**Potential Resource?**
Types of Basalts

New data show that the Apollo landing sites were not ideal for exploring the Moon.

- Apollo sites close to terrane boundaries;
- Samples contain PKT signature;
- Apollo sample collection is not representative of the lunar compositional diversity (Clementine/LP and more recent missions) – sample return needed.

Jolliff et al. (2000) JGR 105, 4197
PKT = Procellarum KREEP Terrane;
FHT = Feldspathic Highlands Terrane

Giguere et al. (2000) MaPS 35, 193
Types of Basalts

Surface TiO₂ map of the Moon. Lunar Reconnaissance Orbiter.
Mare basalts returned by Apollo are very old compared to basalts on Earth.
Nyquist & Shih (1992) GCA 56, 2213-2234

One low-Ti lunar meteorite (NWA-032) is a little younger - ~2.95 Ga.
Borg et al. (2009) GCA 73, 3963-3980
Ages of Mare Basalts

Crater counts used to define the ages of different mare basalt flow fields.

Basalts as young as 1 Ga around Mare Imbrium – center of the Th anomaly.

Hiesinger et al. (2011) GSA Spec. Pap. 477, 1-51
Recent volcanic activity: “IMPs” (Irregular Mare Patches) <100 Ga – associated with the PKT.

The irregular mare patches exhibit sharp, metre-scale morphology with relatively few superposed impact craters larger than ten metres in diameter. Crater distributions from the three largest irregular mare patches imply ages younger than 100 million years, based on chronology models of the lunar surface.

Lacus Felicitatis (north of Mare Vaporum and south of the Apollo 15 landing site)

Preserved Volcanic Features
Lava Tubes (Skylights or Pits)

Marius Hills

Rilles = Collapsed Lava Tubes

Rille @ Apollo 15
Lava Tubes (Skylights or Pits)

Potential Human Habitats

Offers Protection: Meteoroids, Radiation, Diurnal Temperature Swings.

Wagner & Robinson (2014) *Icarus* 237, 52-60
Lava Tubes (Skylights or Pits)

Potential Human Habitats: Marius Hills

Haruyama et al. (2009) GRL 36
Robinson et al. (2012) PSS 69, 18-27
Lava Tubes (Skylights or Pits)

Potential Human Habitats

Layered lava flows in Mare Ingenii

Laying in pit walls

Mare Ingenii

LROC NAC M184810930L (NASA/GSFC/ASU)
### The Regolith of the Moon

**Regolith Composition**

<table>
<thead>
<tr>
<th>Element</th>
<th>Low-Ti Marc Soils</th>
<th>High-Ti Marc Soils</th>
<th>Highland Soils</th>
<th>KREEP Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>60.26</td>
<td>60.30</td>
<td>60.82</td>
<td>60.47</td>
</tr>
<tr>
<td>Si</td>
<td>17.30</td>
<td>15.86</td>
<td>16.31</td>
<td>17.35</td>
</tr>
<tr>
<td>Al</td>
<td>5.56</td>
<td>5.70</td>
<td>10.66</td>
<td>6.48</td>
</tr>
<tr>
<td>Mg</td>
<td>5.53</td>
<td>5.70</td>
<td>3.84</td>
<td>5.39</td>
</tr>
<tr>
<td>Ca</td>
<td>4.44</td>
<td>4.60</td>
<td>5.92</td>
<td>4.43</td>
</tr>
<tr>
<td>Fe</td>
<td>5.85</td>
<td>5.29</td>
<td>1.90</td>
<td>4.47</td>
</tr>
<tr>
<td>Ti</td>
<td>0.66</td>
<td>2.01</td>
<td>0.17</td>
<td>0.62</td>
</tr>
<tr>
<td>Na</td>
<td>0.26</td>
<td>0.31</td>
<td>0.29</td>
<td>0.44</td>
</tr>
<tr>
<td>K</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
<td>0.19</td>
</tr>
<tr>
<td>Mn</td>
<td>0.08</td>
<td>0.07</td>
<td>0.03</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Regolith**: Great source of metals for construction AND oxygen for life support and rocket propellant.
The Regolith of the Moon

Solar Wind and Ilmenite:
Ilmenite (FeTiO$_3$) is a “sponge” that holds on to solar wind species much better than other minerals.

The Regolith of the Moon

Solar Wind and Ilmenite:
Ilmenite ($\text{FeTiO}_3$) is a sponge that holds on to solar wind species much better than other minerals.

Stoenner et al. (1974) PLSC 5th, 2211-2229
The Regolith of the Moon

$^{3}$He mining – follow the maturity?

Optical Maturity Map: Lucey et al. (2000) JGR 105, 20,377-20,386
The Regolith of the Moon

Helium mining – follow the ilmenite ($\text{TiO}_2$)?

$^3\text{He}$ [ppb] from $\text{M}^3\text{TiO}_2$ and Clementine OMAT

Kim et al. (2019) PSS 177

$\text{TiO}_2$ (Sato et al., 2017, Icarus 296, 216-238) overlain on LROC-WAC image (Speyerer et al., 2011, http://wms.lroc.asu.edu/lroc/view_rdr/WAC_GLOBAL)
Summary & Conclusions

• The Apollo & Luna missions returned basaltic samples that were not representative of the whole Moon.
• The Moon remained volcanically active much longer than indicated by the Apollo and Luna missions.
• Younger basalt flows are associated with the PKT and are high-Ti in nature.
• IMPs appear to be more broadly distributed but still within the PKT.
• Preserved volcanic features show the extensive volcanism and potential habitats that will allow humans to survive and thrive on the Moon.
• Mature high-Ti mare regolith represents an important resource that could sustain humanity on the Moon and potentially provide a viable export back to Earth.
Questions??